energies

Article

Analysis of Net-Metering and Cross-Subsidy Effects in South Korea: Economic Impact across Residential Customer Groups by Electricity Consumption Level

Junhyung Kim [1], Keon Baek [2], Eunjung Lee [2] and Jinho Kim [2,*]

[1] Korea Electric Power Corporation, Naju 58322, Republic of Korea
[2] Graduate School of Energy Convergence, Gwangju Institute of Science and Technology, Gwangju 61005, Republic of Korea
* Correspondence: jeikim@gist.ac.kr; Tel.: +82-62-715-5322

Abstract: Recently, thanks to various support mechanisms, residential photovoltaics (PVs) for self-consumption are proliferating at a rapid pace. The net-metering scheme, one of the prevailing support mechanisms for self-consumption PVs, contributes to the proliferation of residential PVs by enhancing the economic benefits of PV adopters, but it suffers from certain disadvantages, such as missing network revenue of utilities and spread of cross-subsidies between the customers. This paper analyzes the cross-subsidy effect of residential PV proliferation across customer groups segmented according to their PV adoption and electricity consumption level under the net-metering scheme in the Korean electricity market. The results show that missing network revenue of utilities increase by about 0.83% for every 1% increase of residential PV penetration, and customers in the lowest usage tier provide more cross-subsidies toward customers in the higher usage tiers as with higher proliferation of residential PVs. In addition, this paper suggests that the cross-subsidy effect between customers can be reduced by introducing a new network charge design that is more consistent with the cost-causality principle as well as targeted deployment policies for self-consumption PVs.

Keywords: net-metering; residential rooftop PV; self-consumption PV; cross-subsidy; missing network revenue

Citation: Kim, J.; Baek, K.; Lee, E.; Kim, J. Analysis of Net-Metering and Cross-Subsidy Effects in South Korea: Economic Impact across Residential Customer Groups by Electricity Consumption Level. *Energies* **2023**, *16*, 717. https://doi.org/10.3390/en16020717

Academic Editor: Surender Reddy Salkuti

Received: 23 October 2022
Revised: 21 December 2022
Accepted: 5 January 2023
Published: 7 January 2023

1. Introduction

With the proliferation of greenhouse gases (GHGs) reduction policies, the electric power industry is rapidly changing from fossil-fuel based generation systems to renewable energy sources (RESs). Thanks to the various economic incentives and political support, the deployment of RESs has been growing faster than any other generation resources for the last two decades; solar photovoltaic (PV) and on-shore wind are among the generation resources with the most economic implications in two-thirds of countries in the world [1–3].

PV has played the most significant role at the center of the current renewable deployment. While the dramatic falling costs have led to a considerable capacity addition of utility-scale commercial PV, a great number of residential, small business, and industrial customers have adopted customer-sited PV to save on bills through the self-consumption of electricity generated during peak price hours. Furthermore, because of the technical and societal benefits as a distributed generator, customer-sited PV receives diverse economic supports such as tax credit and installation subsidies. Consequently, one recent study suggest that global capacity of residential customer-sited PV will have grown by two and a half times by 2024 [4].

Recently, several negative aspects are emerging as the penetration of customer-sited PV increases. First, with the diffusion of customer-sited PV, the decrease in sales volume for centralized utilities have causes declines in their network cost recovery and eventually financial distress [1,5]. Second, tariff adjustments derived from customer-sited PV to recover the incurred network cost have resulted in cross-subsidies between PV adopters and non-PV adopters. In order to recover the incurred fixed network cost through volumetric network charge, utilities have to increase the tariff for the corresponding deficiency. As a results, non-PV adopters are forced to bear additional and unreasonable costs under the current volumetric network charge so that utilities avoid financial distress [6,7].

Numerous prior studies have explored the impact of customer-sited generators on the electric power system, with a particular focus on residential PVs. Some initial studies suggest a measurement compensation framework for customer-sited generators. Hughes and Bell described a taxonomy of different compensating mechanisms on customer-sited generators according to the number of registers, buy-back policy, banking policy, and buy-back rate [8]. Eid et al. suggested a compensation mechanism from the perspective of data measurement, customer consumption and PV production, and billing, such as tariff design and rolling credit [6].

Other studies have analyzed the economic benefits for customers of customer-sited PV under various rate designs. Darghouth et al. showed that the bill saving effect increases as PV adopters have higher consumption levels and smaller PV size as compared to their annual consumption under an inclining block rate [9,10]. Darghouth et al. investigated the impact only in terms of rate design, but both the rate design and wholesale market structure are considered in Darghouth et al. [9,10]. Instead of bill savings, other studies assess the economics of residential PV in terms of levelized cost of electricity (LCOE), ratio between LCOE and electricity tariff, internal rate of return, and payback-time [1,11–15]. Yamamoto compared three compensation mechanisms for customer-sited generators in terms of residential consumer's surplus and social welfare [16]. He showed that there is no one-size-fits-all mechanism, and that the optimal results depend not only upon the mechanism, but also on the characteristics of households.

The cost recovery issues of utility or distribution system operators (DSOs) have been explored by some other studies. Many studies agree that progressive deployment of residential PVs with net-metering will lower the network cost recovery under current rate design and, furthermore, may be the trigger point of utilities' death spiral, depending on the regulation framework, utilities' rate structure and PV penetration level [1,5,6,14,17–22]. With regard to cost recovery, researchers have considered how to identify rate designs that can avoid or minimize the effect of customer-sited PV under net-metering. While different rate designs are examined as alternatives to current volumetric charge and net-metering, the current conclusion is that the optimal solution varies with surrounding circumstances, such as load profiles, PV system size, PV performance and so on [1,23,24]. A new study has also addressed cost recovery issues of distribution utilities by combining rate design with real-time consumption date of advanced metering infrastructure (AMI) [25].

Another research topic on self-consumption PVs is the cross-subsidy issue between customer groups. Under the cost-of-service regulation framework, self-consumption PVs with net-metering eventually entail cross-subsidy issues because someone in the electric power system, usually non-PV adopters, bears an additional charge to support the utilities' missing network revenue that was caused by PV adopters [6,26–29]. It is very important for regulators and utilities to understand the precise dynamics of this issue from the perspective of social welfare distribution, in that non-PV adopters tend to be the economically disadvantaged [30]. To solve this problem, additional studies have been conducted to suggest a new rate design [15,25,31,32]. However, thus far, few studies have quantified the extent to which non-PV adopters subsidize PV adopters, and still fewer studies have considered the cross-subsidies between customers with respect to their electricity usage.

This study mainly focuses on identifying and quantifying which consumer groups bear the missing network revenue attributable to the deployment of residential PV and how much of the network cost is paid by each group. This study classifies consumers into six groups according to their PV adoption and electricity consumption level and simulates the bill savings effect, PV penetration effect, and rate design effect of residential PV by each consumer group. Our results highlight that non-PV adopters in the lowest usage tiers only pay the additional charge to cancel out the undue benefit of PV adopters in all usage tiers who do not pay a fair cost for network service, and that customers in the lowest usage tier bear more network costs under higher PV penetration. These results were simulated based on hourly load profiles of nearly residential customers and monthly consumption data of 1350 net-metering customers before subscription of net-metering to simulate the PV adoption rate by consumption level.

The main contributions of this study are as follows:

- This study is the first to quantitatively analyze the cross-subsidy effect of self-consumption PVs between customers, which means that non-PV adopters financially support the network cost that the PV adopters should have paid for from the perspective of their electricity consumption level (usage tiers).
- The results in this study are based on comprehensive real data sets that represent the key characteristics of electricity demand, self-consumption, and the PV installation level of residential customers in South Korea.
- Alternative policies are suggested to simultaneously mitigate the side effects of self-consumption PVs under net-metering scheme and meet the environmental goal of deploying self-consumption PVs.

The rest of the paper is organized as follows. Section 2 provides this study's data, especially related to residential tariff structure, customer loads, PV installation and generation. Section 3 explains the simulation structure and measures. Section 4 presents the simulation results and interpretations. Section 5 proposes the policy implications and conclusions.

2. Data

2.1. Korea's Electricity Billing System

As of 2022, Korea's electricity bill system is composed of four components: demand charge, energy charge, climate change and environmental charge (CCEC), and fuel cost pass-through adjustment rate (FCPAR). The last two of these components were introduced in 1 January 2022, and thus only demand charge and energy charge are considered in this study. Table 1 shows the description of each component as of 2022 [33].

Table 1. Overview of Korea's electricity bill system.

Component	Description	Unit
Demand charge	Factor to recover fixed costs related to electric power faciclities such as transmission and distribution network	kW
Energy charge	Factor to recover variable costs such as fuel costs incurred in proportion to the amount of electricity consumption	kWh
CCEC	The sum of Renewable Portfolio Standards (RPS) cost, Emission Trading System (ETS) cost and so on	kWh
FCPAR	Factor to reflect changes in international fuel prices, mainly liquified natual gas (LNG), on a quarterly basis	kWh

2.2. Residential Tariff Description

The effects of residential PV in this study were analyzed based on the rate structure for low-voltage customer offered by the Korea Electric Power Corporation (KEPCO) from January 2018 to December 2018. Basically, the residential rate consists of two components: the demand charge per household to recover about 58% of network costs, which are incurred from transmission and distribution facilities to deliver the electricity produced or procured in the wholesale market from the power plants to the customer; and the energy charge per kWh (volumetric) to recover the rest of network cost, power purchasing cost in the wholesale market and retail cost in 2018. Both the demand charge and the energy charge are imposed in the form of a three-tier inclining block rate system depending on monthly consumption level. The monthly consumption of an individual customer is classified by every 200 kWh. For example, usage tier 1 rate is applied to first 200 kWh, which accounts for about 80% of average monthly consumption of total residential customers, followed by usage tier 2 rate for an additional 200 kWh and usage tier 3 rate for consumption over 400 kWh [34].

The purpose of the demand charge is to recover the network cost that is nearly incurred regardless of electricity consumption. Although it seems reasonable to bill the demand charge according to the contracted capacity (usually 3 kW for residential customers in Korea), the demand charge actually depends on the monthly consumption level. In usage tier 1, the monthly demand charge per household is $0.8270 and increases smoothly to $1.4541 for usage tier 2, but it rises dramatically to $6.6346 for usage tier 3.

Unlike the commercial and industrial customers offered with Time-of-Use (TOU) rate, the residential tariff is a flat rate within the same usage tier but inclines between usage tiers. The lowest usage tier 1 rate is $0.0848/kWh, and the highest usage tier 3 rate is $0.2550/kWh, which is designed to increase linearly according to the consumption level. In order to provide residential customers with a more diverse choice, KEPCO began a demonstrative TOU rate project for about 2000 households in 2019. While the rate of commercial and industrial customers depends on their contracted capacity, that of residential customers is determined by voltage level.

2.3. Customer Load and PV Generation Profile

It is essential to obtain gross and net data for consumption and generation to analyze the effects of PV under net-metering. However, as in many other jurisdictions, the current metering practice in Korea for residential customers with PV is to install one bi-directional metering device that only measures customers' net consumption from the grid when PV generation is insufficient, and PV net generation fed into the grid when PV produces more electricity than customers consume. The possibility of rebound effect, where customers increase their electricity consumption after PV installation, means that limited availability of gross consumption and generation data remains an obstacle to an in-depth study of net-metering issues [35,36]. Synthetic net load profiles after PV installation are also obtained in this study from separate gross customer load profiles without PV system and gross PV generation profiles. The period of customer load and PV generation data in this study spans the 12 months from January 2018 to December 2018.

2.3.1. Customer Load

This study relies on the hourly gross load data of 2959 residential customers randomly selected after data cleansing. As customers in the higher usage tier have greater economic benefit under volumetric energy charges and net-metering [9,10], the sample is constructed similarly to the actual customer numbers and monthly consumption by usage tier of total residential customer to reliably evaluate the cross-subsidy effects of residential PVs. The numbers of customers for usage tiers 1–3 are 1192, 1447 and 320, respectively, and average monthly consumption is 110.56 kWh, 277.09 kWh and 511.74 kWh respectively. A summary of customer load data is shown in Table 2.

Table 2. Characteristics of sample and population for residential customer in Korea by usage tier.

	Average Monthly Consumption	Sample (Residential Customers)		Population (Residential Customers)	
		Proportion	**Monthly Consumption**	**Proportion**	**Monthly Consumption**
Usage tier 1	Below 200 kWh	40.3%	110.56	40.4%	101.50
Usage tier 2	200~400 kWh	48.9%	277.09	48.4%	299.28
Usage tier 3	Above 400 kWh	10.8%	511.74	11.4%	533.30

2.3.2. PV Installation Level

As of the end of 2018, 341,523 residential customers (2.23% of total residential customers) had installed self-consumption generators, 99.7% of them had adopted PV system. The total and average PV system sizes were 1,055,326 kW and 3.10 kW, respectively. The geographical distribution of residential PV systems differs slightly from that of residential customers. Seoul and the metropolitan area, where 42.5% of total residential customers reside, account for only 23.0% of total residential customers with PV systems because the majority of residential types are multi-family houses such as apartments, which are not favorable for PV systems installation. In fact, 49.5% of the total residential customers with PV systems are located in Gyeongsang and Joella Provinces, which have the best solar radiation; this accounts for 39.5% of total residential customers.

To obtain reliable and applicable PV installation levels rate for each usage tier, we examined the monthly consumption data of 22,516 residential customers who installed a PV system and subscribed to the net-metering system offered by KEPCO from 2012 to 2019. We then used the average monthly consumption data of 1350 customers who had at least 12 consecutive months of consumption data just before they were opted in to the net-metering. As a result, this study assumes that, of the total PV installers, 15.8% are usage tier 1 customers, 68.7% are usage tier 2 customers and 15.5% are usage tier 3 customers. From the perspective of PV installation level by usage tier, 0.9888% of usage tier 1 customers, 3.6422% of usage tier 2 customers and 3.7117% of usage tier 3 customers had installed PV systems.

2.3.3. PV Generation

As stated above, it is practically impossible at this point to obtain a reliable gross generation profile of residential PVs in Korea. As an alternative approach, this study developed and applied a synthetic hourly generation profile that used a representative 3 kW PV system for residential customers and multiplied hourly capacity factors based on hourly generation and capacity data of all commercial PVs that are traded in the Korean wholesale power market from January 2018 through December 2018. As of the end of 2018, the capacity of commercial PVs was 7130 MW, which accounts for 79.8% of total PVs in Korea [37]; this is what was used in this paper. The annual capacity factor of commercial PV used in this study is 16.8%, about 1–3% higher than what is usually expected for residential and small-sized PVs in Korea [38].

3. Simulation Structure and Measures

This study focuses on analyzing the effects of customer-sited PV with net-metering: bill saving effect on PV adopters, network cost recovery effect on network service providers such as DSO and cross-subsidy effects among customers. As shown in Figure 1, this study adopts the simulation of 2959 residential customers, and we classify the sample into 6 customer groups according to the average monthly consumption level (3 usage tiers) and PV adoption (PV adopter vs. non-PV adopter). While the KEPCO is a vertically integrated utility that operates in all levels of the supply chain from generation, transmission and distribution to retail businesses, it is assumed to form an independent network service provider in this study and hence cannot receive any subsidies from other business areas.

3.1. Scenario

3.1.1. Net-Metering Scenario

Net-metering customers pay bills only for their billing-purpose consumption, which equals the electricity imported from the grid when they need more electricity after self-consumption from their PV generation, less credits that are paid for the excess PV generation exported to the grid and are eligible to offset their bills. This study assumes three net-metering scenarios with different PV penetration levels of 2.5%, 5.0% and 10.0% to find the effects of progressive deployment of self-consumption PVs in the future, and compare the results with zero PV system scenario (scenario 1 in Table 3).

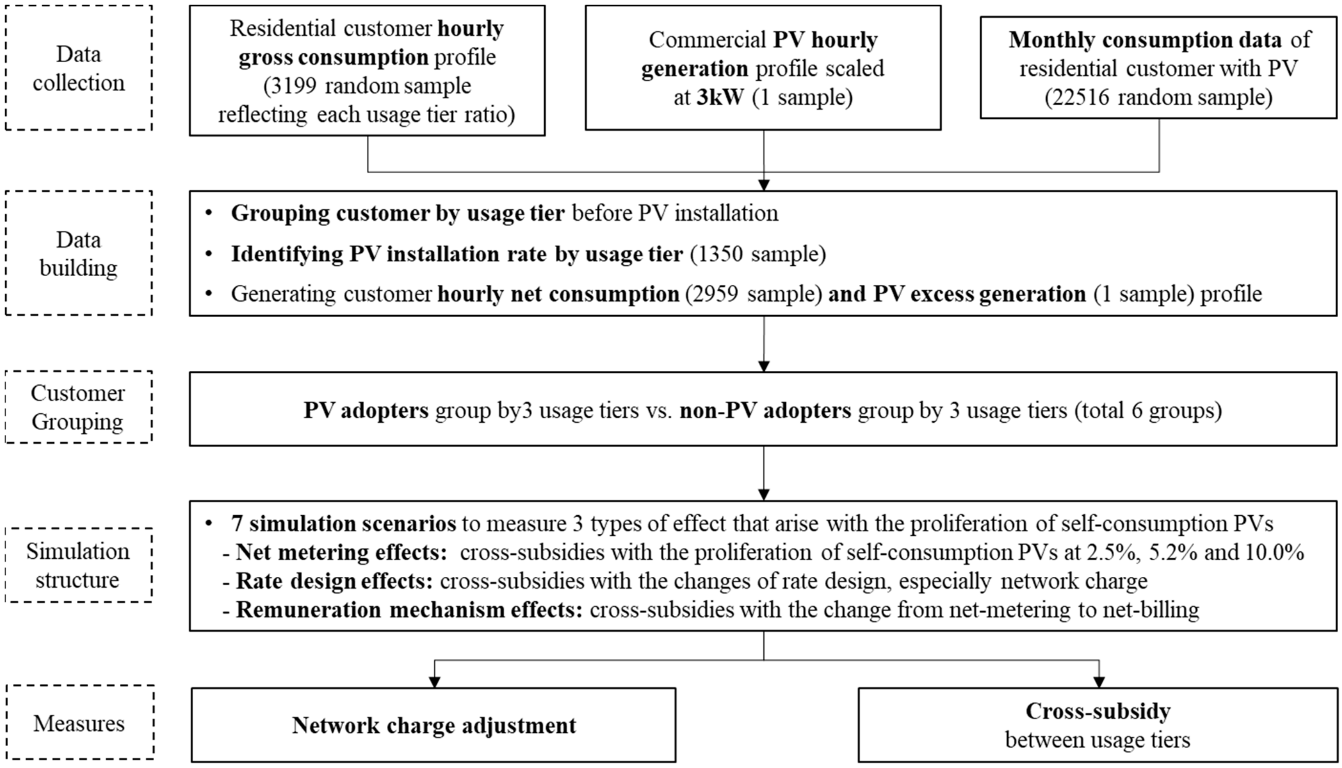

Figure 1. Summary of analysis structure.

Table 3. Simulation scenarios.

Scenarios	Rate Structure	Residential PV Penetration	Number of PV Adopters by Usage Tiers (1:2:3)			Network Charge Structure	Missing Network Revenue Recovery
S1	demand, energy	0%		n.a.		demand, energy	n.a.
S2	demand, energy	2.5%	12	51	11	demand, energy	energy charge
S3	demand, energy	5.0%	23	102	23	demand, energy	energy charge
S4	demand, energy	10.0%	47	203	46	demand, energy	energy charge
S5	demand, energy	2.5%	12	51	11	demand	energy charge
S6	demand, energy, capacity	2.5%	12	51	11	demand	capacity charge
S7	demand, energy	2.5%	22	43	9	demand, energy	energy charge
S8	demand, energy	2.5%	37	30	7	demand, energy	energy charge

3.1.2. Alternative Scenarios

The current cost structure that recovers fixed network costs through volumetric energy charges inevitably causes a network cost recovery issue because the electricity consumption of PV adopters from the grid will decrease progressively as the residential PV penetrates. This study suggests two alternative approaches to address these unintended side-effects.

As one alternative approach, this paper introduces two new network rate designs that can recover 100% of the network cost by using new quasi-fixed demand charges calculated from the forecasted sales volume (scenarios 5–6 in Table 3). However, even with the new demand charge, the network charge adjustment process is required to recover missing network revenues because of the difference in forecasted and actual PV penetration. These missing network revenues are recovered by the volumetric energy charge in scenario 5, as in scenarios 2–4.

In addition, imposing capacity charges to recover missing network revenues is a reasonable alternative scenario, in that network cost is closely associated with each customer's peak contribution. Thus, three-part rate structure is simulated in scenario 6, including a capacity charge that is billed according to each customer's peak contribution (Equation (4)).

$$\text{Three-part rate structure} = Td_j + Te_j + Tc_j \tag{1}$$

$$ne = \frac{\sum_j nt \times cb_j - \sum_j Td_j}{\sum_j cb_j} \tag{2}$$

$$D = \sum_j \left(Td_{j\ \ without\ PV} - Td_{j\ \ with\ PV} \right) + nc_e \times \sum_j \left(cb_{j\ \ without\ PV} - cb_{j\ \ with\ PV} \right) \tag{3}$$

$$Tc_j = D \times \frac{pd_j}{\sum\ pd_j} \tag{4}$$

Here, Td_j, Te_j and Tc_j are the demand, energy, and capacity charges for customer j, respectively. On a per kWh basis, total network charge (nt) equals the sum of network charges in the demand charge (nd) and energy charge (ne). With the proliferation of customer-sited PVs and net-metering, network service providers with volumetric ne inevitably face missing network revenue (D) because of the decrease in billing-purpose consumption (cb_j) that equals the net consumption minus the available credit until the month. To address this problem, capacity charge (Tc_j) is proposed as an additional rate component according to each customer's peak demand contribution to the total peak demand $(pd_j / \sum\ pd_j)$.

On the other hand, a sophisticated deployment policy on rooftop PVs is considered as the second alternative approach. Given the previous study which showed that customers in higher usage tiers are the biggest beneficiaries of rooftop PVs, customers in higher usage tiers tend to install more self-consumption PVs in Korea (Section 2.3.2) [9]. Therefore, this study analyzes whether the increase in PV adoption level for customers in a lower usage tier can make meaningful impacts on cross-subsidy effect between customers by usage tiers. The proportion of usage tier 1 customers among PV adopters, which was originally 15.8% in scenario 2, increases up to 30% in scenario 7 and 50% in scenario 8, with the total number of PV adopters unchanged. The number of PV adopters in usage tiers 2 and 3 are calculated by Equation (5).

$$N'_{PA,\ i} = N_{PA,i} - \left(N'_{PA,1} - N_{PA,1}\right) \times \frac{N_{PA,\ i}}{\sum_{i=2}^{3} N_{PA,i}} \tag{5}$$

where, $N'_{PA,i}$ is the revised number of PV adopters in usage tier i in scenarios 7 and 8, and $N_{PA,i}$ is the initial number of PV adopters in usage tier i in scenario 2. Numbers below the decimal point are rounded up to the nearest integers.

3.2. Measure

Three measures that reflect the interests of three stakeholders in the electric power industry—the customer, utility and regulator—are proposed in this study to analyze the effect of residential PV under the cost-of-service regulation that allows utilities (network service providers) to recover their revenue requirement including investment, operation and maintenance expenditure and reasonable returns.

3.2.1. Network Charge Adjustment

The impact of residential PVs on network cost recovery is an important issue for the financial sustainability and reliability of network service providers. To recover the missing network revenue derived from self-consumption with residential PVs, network service providers should impose an additional network charge on customers (Δne). This study assumes the Δne is applied as a form of energy charge according to the billing-purpose consumption (volumetric charge), except for scenario 6 (Table 3) where the additional network charge is billed on a peak consumption (kW) basis.

$$\Delta ne = \frac{D}{\sum_j cb_{j \in \forall i}} \tag{6}$$

3.2.2. Cross-Subsidy

The main focus of this study is to analyze cross-subsidies among the customer groups caused by the deployment of residential PV, which describes the unreasonable pass-on of network service costs among customer groups under cost-of-service regulation. Equation (7) give us the network charge distribution for usage tier i. The ne' in Equation (7) that equals the sum of ne in Equation (2) and Δne in Equation (6) represents the network charge in the energy charge required to recover the entire network cost. Comparing the network charge distribution of each customer group before and after PV installation indicates the degree of cross-subsidy (Equation (8)).

$$\text{Network charge distribution for usage tier } i\ (ND_i) = \frac{\sum_j \left(Td_{j\in i} + ne' * cb_{j\in i}\right)}{\sum_i \sum_j \left(Td_{j\in i} + ne' * cb_{j\in i}\right)} \tag{7}$$

$$\text{Cross-subsidy for usage tier} = ND_i \text{ after PV system installation} - ND_i \text{ before PV system installation} \tag{8}$$

4. Results and Interpretations

4.1. Effect of PV Penetration (Scenario 1–4)

Table 4 shows a linear relationship between PV penetration and missing network revenue, but the detailed results depend on the rate design. Under the volumetric network charge, the decrease in PV adopters' electricity imports from the grid (net consumption) inevitably brings about the missing network revenue, compared with the network revenue allowed or required by regulators. Under the current network charge design as used in this study, where 42% of the total network cost is collected through volumetric energy charge and 58% through demand charges, missing network revenues increase by 2.07%, 4.20% and 8.43% of allowed network revenue under the assumption of a 2.5%, 5.0% and 10.0% PV penetration, respectively. When assuming that 100% of network charge is recovered through volumetric energy charge (100% volumetric network charge), this missing network revenue would be further exacerbated from 2.80% to 11.20% of allowed network revenue. These results suggest that missing network revenue would increase with higher residential PV penetration, but that it could be alleviated with demand charges; in this study, that amounts to approximately one-quarter compared with the 100% volumetric network charge before network charge adjustment.

Table 4. Missing network revenue by PV penetration level under current rate design and 100% energy charge.

	S1	S2	S3	S4
PV penetration	0.00%	2.50%	5.00%	10.00%
Missing network revenue				
- with current rate design	-	2.07%	4.20%	8.43%
- with 100% volumetric network charge	-	2.80%	5.64%	11.20%

The simulation results show that the cross-subsidies between usage tiers, especially from lower usage tiers to higher usage tiers, are progressively increasing as residential PV proliferates. As per Table 5, while the network charge distribution for only usage tier 1 customers increases from 19.4480% in scenario 1 to 20.8282% in scenario 4, those of usage tiers 2 and 3 decline from 52.0882% to 51.7179%, and from 28.4638% to 27.4539%, respectively, between the same scenarios. The most notable result is that customers in usage tiers 2 and 3 who contributed more to the network peak demand pay less network charge by 0.71% and 3.55%, respectively, in scenario 4, and customers in usage tier 1 who contributed the least to the network peak demand pay more network charge by 7.10% in scenario 4, compared to the results in scenario 1.

Table 5. Network charge distribution by PV penetration, usage tier and PV adoption.

Usage Tier	PV Adoption	S1	S2		S3		S4	
		Network Charge Distribution	Network Charge Distribution	Cross-Subsidy	Network Charge Distribution	Cross-Subsidy	Network Charge Distribution	Cross-Subsidy
1	PV adopters	0.1891%	0.1080%	−0.0811%	0.2069%	−0.1584%	0.4260%	−0.3267%
	Non-PV adopters	19.2589%	19.6525%	0.3936%	19.8985%	0.8158%	20.4023%	1.7070%
	Sub-total	19.4480%	19.7604%	0.3124%	20.1054%	0.6574%	20.8282%	1.3803%
2	PV adopters	1.8310%	0.5266%	−1.3044%	1.0496%	−2.5555%	2.0998%	−5.0779%
	Non-PV adopters	50.2572%	51.4411%	0.1839%	50.8696%	2.3865%	49.6181%	4.7076%
	Sub-total	52.0882%	51.9677%	−0.1204%	51.9193%	−0.1689%	51.7179%	−0.3703%
3	PV adopters	1.0726%	0.3967%	−1.6760%	0.8006%	−1.4615%	1.6202%	−2.9238%
	Non-PV adopters	27.3912%	27.8752%	0.4839%	27.1747%	0.9730%	25.8337%	1.9138%
	Sub-total	28.4638%	28.2718%	−0.1920%	27.9753%	−0.4885%	27.4539%	−1.0100%

These paradoxical results can be explained by the characteristics of the demand charge, the remuneration mechanism of the net-metering scheme, and the PV adoption level. First, the reductions in network charge for PV adopters in usage tier 1 are strictly limited to only lower energy charges because their demand charge still remains at the same level even after PV installation; meanwhile, non-PV adopters unintentionally bear additional network charges through Equation (6). Consequently, the overall network charge distribution of usage tier 1 customers increases as the PV systems proliferate. On the other hand, for usage tiers 2 and 3 customers, the overall network charge distributions decrease because the reduction in network charge for PV adopters is derived from a drop in both demand charge and energy charge that exceeds the increase in network charge of non-PV adopters through Equation (6).

Second, these consequences also arise from the asymmetric remuneration mechanism of net-metering under inclining block rate that compensates customers' PV generation at higher (lower) retail prices for higher (lower) usage tier customers, as shown in Table 6. Finally, the difference in PV adoption rates between usage tiers is one of the important factors that leads to these results. The shift from non-PV adopters to PV adopters in usage tier 1 is the lowest among all usage tiers because customers in usage tier 1 already consume the least electricity per household before PV installation and have the least interest in installing PV systems for self-consumption, as shown in Table 2 and Section 2.3.1. As a result, only customers in usage tier 1 pay more network charges through network charge adjustment (Equation (6)) than they would reasonably pay without the proliferation of PV systems.

Table 6. Changes of annual network charge and net consumption between scenarios 1 and 2.

Usage Tier	Change of Annual Network Charge per Household * (USD)						Shift to PV Adopter Group, % of Consumption in Scenario 1
	PV Adopters			Non-PV Adopter			
	Demand Charge	Energy Charge	Total	Demand Charge	Energy Charge	Total	
1	−0.10	−7.35	−7.46	0.00	0.37	0.37	0.54%
2	−9.85	−18.36	−28.21	0.00	0.94	0.94	1.60%
3	−43.48	−24.30	−67.79	0.00	1.73	1.73	1.30%

* Negative values indicate that the network charge in scenario 2 decreases compared to that in scenario 1, and positive values indicates vice versa.

4.2. Effect of Network Charge Design (Scenario 2 and 5–6)

Cross-subsidies with self-consumption PVs are fundamentally derived from the discordance between how network costs arise and how they are recovered. In this section, this study analyzes the effect of alternative rate designs that can reduce this discordance in cross-subsidies.

In scenario 5, a new rate design is introduced in which 100% of the network cost is recovered through new demand charges determined according to forecasted sales volume, which is more consistent with the cost-causality principle because the demand charge is designed to recover fixed costs of total electricity supply costs in its nature. However, even in this case, missing network revenue still inevitably arises because PV adopters' usage tiers change if additional self-consumption PVs are installed and are assumed to be recovered through a uniform level of additional energy charge to all customers (Equation (6)).

The results are shown in Table 7. First, with a newly designed demand charge that allows 100% of network costs to be recovered based on ex-ante sales volume (scenario 5), the cross-subsidy effect decreases by 26.25% compared to scenario 2, from 2.0614% to 1.5203%. This is attributable to the characteristics of quasi-fixed demand charges, which bears the same network charge in the same usage tier, in contrast to the current rate design in which the network charge decreases even if the net consumption decreases by only every kWh. Second, the magnitude of cross-subsidy for PV adopters in usage tier 1 is smaller than that in scenario 2. This can be explained by the rigidity of the demand charge, especially for PV adopters in usage tier 1. According to this study, the number of months when PV adopters in usage tier 1 paid the same demand charge as before is 142 months of the total 144 months (98.61%), 96 months of the total 612 months (15.69%) for PV adopter in usage tier 2, and 32 months of the total 132 months (24.24%) for PV adopters in usage tier 3.

Table 7. Network charge distribution and cross-subsidies by usage tiers under the new network charge designed to recover 100% of network costs plus network charge adjustments through energy charge (scenario 5) and through capacity charge (scenario 6).

		S2		S5		S6	
	Usage Tier	**Network Charge Distribution**	**Cross-Subsidy**	**Network Charge Distribution**	**Cross-Subsidy**	**Network Charge Distribution**	**Cross-Subsidy**
PV adopters	1	0.1080%	−0.0811%	0.1740%	−0.0151%	0.1775%	−0.0116%
	2	0.5266%	−1.3044%	0.8794%	−0.9515%	0.9087%	−0.9223%
	3	0.3967%	−0.6760%	0.5190%	−0.5537%	0.5239%	−0.5487%
	Sub-total	1.0313%	−2.0614%	1.5724%	−1.5203%	1.6101%	−1.4826%
Non-PV adopter	1	19.6525%	0.3936%	19.5703%	0.3114%	19.6658%	0.4069%
	2	51.4411%	1.1839%	51.1252%	0.8680%	51.0829%	0.8257%
	3	27.8752%	0.4839%	27.7321%	0.3409%	27.6412%	0.2500%
	Sub-total	98.9687%	2.0614%	98.4276%	1.5203%	98.3899%	1.4826%

Under scenario 6 where network charge adjustments are billed according to individual customers' peak contributions, the cross-subsidy effect is 1.4826%, slightly improved compared to the results of scenario 5. However, the one thing noteworthy in the results of scenario 6 is that the cross-subsidies of only usage tier 1 customers in the non-PV adopter group increase compared to the results of scenario 2 as well as scenario 5 because their peak reductions and PV installation levels are lower than those of usage tier 2 and 3 customers (Section 2.3.2). Specifically, the average peak reductions per PV adopter for usage tier 1, 2, and 3 customers are 0.0941, 0.2622, and 0.5193 kW, respectively. This means that non-PV adopters in usage tier 1 who do not install PV systems because of the installation cost and lack of economic incentive would unintentionally subsidize other customers more than in the case of net-metering scheme, if the capacity charge based on individual peak contribution is introduced.

4.3. Effect of PV Adoption Level by Usage Tiers (Scenario 2 and 7–8)

Under the inclining block rate and net-metering scheme, asymmetric compensation for PV adopters in higher usage tiers will lead to a dramatic decrease in the demand charge to recover the costs of existing network facilities; this increases missing network revenues of utilities and cross-subsidies between customers. To mitigate these problems, network charge redesign is examined in Section 4.2 to impose higher network charges upon customers in higher usage tiers who contribute more to the network investment. However, this approach could also deteriorate the economics of self-consumption PVs and hinder the proliferation of RESs.

Therefore, in this section, this study analyzes scenarios where the proportion of PV adopters in lower usage tiers increases with the same capacity of self-consumption PVs to mitigate the cross-subsidy effect and contribute to the proliferation of self-consumption PVs to achieve the carbon-neutrality goal. The results suggest that a sophisticated policy to encourage customers in lower usage tiers to install more self-consumption PVs can improve cross-subsidies between customers. As shown in Table 8, the cross-subsidy effect is reduced by 13.87%, from 2.0614% in scenario 2 to 1.7755% in scenario 7, where 30% of the total PV adopters belongs to usage tier 1 customers. In addition, when the proportion of PV adopters belonging to usage tier 1 increases up to 50% (scenario 8), the cross-subsidy effect could be reduced by 28.56% compared to the result of scenario 2, which is the largest reduction in cross-subsidies among the scenarios presented in this study. These results occur because the customers belonging to usage tier 1 pay almost the same demand charge even after PV installation and have the least effect on missing network revenue issues compared to customers in higher usage tiers. According to this study, the missing network revenue is 1.78% in scenario 7 and 1.48% in scenario 8, which is lower than 2.07% in scenario 2, assuming an identical PV penetration rate.

Table 8. Network charge distribution and cross-subsidy by usage tiers under increases in PV adoption level in usage tier 1.

		S7			S8		
	Usage Tier	**Customer Number**	**Network Charge Distribution**	**Cross-Subsidy**	**Customer Number**	**Network Charge Distribution**	**Cross-Subsidy**
PV adopters	1	22	0.1970%	−0.1512%	37	0.2976%	−0.2912%
	2	43	0.4427%	−1.0858%	30	0.3031%	−0.7577%
	3	9	0.3272%	−0.5385%	7	0.2491%	−0.4238%
	Sub-total	74	0.9678%	−1.7755%	74	0.8497%	−1.4727%
Non-PV adopter	1	1170	19.4339%	0.3350%	1155	19.1324%	0.2732%
	2	1404	51.5820%	1.0223%	1417	51.8794%	0.8520%
	3	311	28.0163%	0.4182%	313	28.1385%	0.3475%
	Sub-total	2885	99.0322%	1.7755%	2885	99.1503%	1.4727%

Finally, Table 8 shows a significant improvement in the cross-subsidy for usage 1 customers. Comparing scenarios 6 and 8 with similar cross-subsidy effect from non-PV adopters to PV adopters, it can be seen that the cross-subsidy for PV adopters in usage tier 1 increases significantly, whilst the cross-subsidy from non-PV adopters in usage tier 1 decreases significantly. These results indicate that increasing the proportion of demand charges helps to address the cross-subsidy issue between PV adopters and non-PV adopters, but it also worsens social welfare distribution by offering excessive financial support for PV adopters in higher usage tiers.

5. Policy Implications and Conclusions

Under the currently prevailing volumetric network charge and net-metering, utilities will inevitably face a gradually increasing problem of "missing network revenue" with the proliferation of residential PVs for self-consumption. The simulation results with the rate structure offered by KEPCO shows that the network revenue would decrease by 0.83–0.84% for every 1% of residential PV penetration (scenario 1–4 in Table 3). These results indicate that the proliferation of self-consumption generators may act as a significant financial threat to utilities, especially network service providers. While the network charge adjustment processes are necessary to avoid the financial disruption of network service as public goods, cross-subsidies between customer groups occurs depending on their PV adoption and the amount of electricity usage in this process [1]. The main findings of this study are as follows:

- Under the inclining block rate, the asymmetric remuneration mechanism of net-metering for self-consumption PVs and the existence of quasi-fixed demand charge will cause unintended cross-subsidies from lower usage customers—typically the economically underprivileged—to higher usage customers (Table 5). In particular, from the perspective of demand charge, the marginal benefits of every kWh for PV adopters in usage tier 1 are almost zero.
- To mitigate the cross-subsidy effect on customers that is caused by the proliferation of self-consumption PVs, it is necessary to increase the proportion of fixed-charges in the network charge and change the rate design in a way that conforms more to the cost-causality principle. For example, the cross-subsidy effect can be reduced by up to 25% in the Korean market by simply increasing the proportion of demand charges in the network charge.
- The cross-subsidy effect can be alleviated by changing the deployment policy for self-consumption PVs even under the current rate design. Targeted deployment to increase the PV adoption level of customers in usage tier 1 who have a relatively low impact on missing network revenue after PV installation could contribute to reducing the cross-subsidy effect as much as network charge redesign.

Thanks to global GHGs reduction policies and the rapid declines in PV installation costs, the proliferation of residential PVs is also increasing at a rapid pace. In addition, various public and private support mechanisms for RESs are emerging, which reflects the environmental and social benefits such as reducing GHGs and avoiding investments in power systems. However, previous studies have criticized the most representative support mechanism, the net-metering scheme with prevailing volumetric network charge, in terms of its compensation structures for self-consumption PVs, unintended cross-subsidies from non-PV adopters to PV adopters and the possibility of financial distress to incumbent utilities.

However, it should be noted that economic inequality between customers, depending on their PV adoption and electricity consumption level, can be intensified in this course of action. To address this issue, systematic approaches are needed from the perspective of regulation, rate design and utilities' business model. These approaches include the following.

First, regulators should contemplate the introduction of new support mechanisms for self-consumption PVs, such as a direct support for PV installation differentiated by income and consumption level to incentivize usage tier 1 customers. This study shows that a sophisticated deployment policy can help address utilities' missing network revenue issues and customers' cross-subsidy issues (Section 4.3). If the installation of additional metering devices for self-consumption PVs is economically feasible, a change in the compensation mechanism for self-consumption PVs is a good solution. Although the net-billing scheme is a perfect alternative, the cross-subsidy issue can be largely resolved by adjusting the compensation price for the electricity generated from self-consumption PVs.

Second, if it is necessary to maintain an indirect support mechanism through retail rates, the introduction of new rate designs would be needed to recover all network costs from the PV adopters, regardless of the changes in their electricity consumption from utilities. For example, the proportion of fixed network charges could be raised to recover

100% of network costs according to the expected annual consumption or peak demand of individual customers. Another method is to bill customers a fixed surcharge to cover the expected missing network revenue according to the actual peak demand, regardless of their energy consumption. However, these fixed charge approaches have several drawbacks that may negatively affect the proliferation of RESs by causing the economic deterioration of self-consumption RESs and they do not provide any incentive for the efficient utilization of network assets [6,39].

Lastly, strategic approaches to developing a new business model to offset the missing network revenue and maximize the utilization of existing network assets are required [20]. A good example of a new business model is to provide customers with a peer-to-peer transactions system for excess generation and impose a reasonable network charge on them, instead of current direct purchase from the utility. Furthermore, network investment plans based on the current centralized one-way power system from generators to end-users will no longer be sustainable in a future power system oriented toward distributed energy resources (DERs), and new innovative plans to supply maximum power with minimum investments that take into accounts changes in behind-the-meter (BTM) will be required.

Author Contributions: Conceptualization, data curation, and writing—original draft preparation, J.K. (Junhyung Kim); writing—review and editing, K.B. and E.L.; supervision, J.K. (Jinho Kim). All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. 20226210100020 and No. 20226210100070).

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Castaneda, M.; Jimenez, M.; Zapata, S.; Franco, C.J.; Dyner, I. Myths and facts of the utility death spiral. *Energy Policy* **2017**, *110*, 105–116. [CrossRef]
2. BNEF. *1H 2020 LCOE Update–Renewables Chase Plunging Commodity Prices*; BNEF: New York, NY, USA, 2020.
3. IRENA. *Renewable Power Generation Costs in 2019*; IRENA: Anu Dhabi, United Arab Emirates, 2020.
4. IEA. *Renewables 2019; Analysis and Forecast to 2024*; IEA: Paris, France, 2019.
5. Satchwell, A.; Mills, A.; Barbose, G. Regulatory and ratemaking approaches to mitigate financial impacts of net-metered PV on utilities and ratepayers. *Energy Policy* **2015**, *85*, 115–125. [CrossRef]
6. Eid, C.; Guillén, P.F.; Marín, P.F.; Hakvoort, R. The economic effect of electricity net-metering with solar PV: Consequences for network cost recovery, cross subsidies and policy objectives. *Energy Policy* **2014**, *75*, 244–254. [CrossRef]
7. Ruester, S.; Schwenen, S.; Batlle, C.; Pérez-Arriaga, I. From distribution networks to smart distribution systems: Rethinking the regulation of European electricity DSOs. *Util. Policy* **2014**, *31*, 229–237. [CrossRef]
8. Hughes, L.; Bell, J. Compensating customer-generators: A taxonomy describing methods of compensating customer-generators for electricity supplied to the grid. *Energy Policy* **2006**, *34*, 1532–1539. [CrossRef]
9. Darghouth, N.R.; Barbose, G.; Wiser, R. The impact of rate design and net metering on the bill savings from distributed PV for residential customers in California. *Energy Policy* **2011**, *39*, 5243–5253. [CrossRef]
10. Darghouth, N.R.; Wiser, R.; Barbose, G. Customer economics of residential photovoltaic systems: Sensitivities to changes in wholesale market design and rate structures. *Renew. Sust. Energ. Rev.* **2016**, *54*, 1459–1469. [CrossRef]
11. Comello, S.; Reichelstein, S. Cost competitiveness of residential solar PV: The impact of net metering restrictions. *Renew. Sust. Energ. Rev.* **2017**, *75*, 46–57. [CrossRef]
12. Bertsch, V.; Geldermann, J.; Lühn, T. What drives the profitability of household PV investments, self-consumption and self-sufficiency? *Appl. Energy* **2017**, *204*, 1–15. [CrossRef]
13. Solano, J.C.; Brito, M.C.; Caamaño-Martín, E. Impact of fixed charges on the viability of self-consumption photovoltaics. *Energy Policy* **2018**, *122*, 322–331. [CrossRef]
14. Iglesias, C.; Vilaça, P. On the regulation of solar distributed generation in Brazil: A look at both sides. *Energy Policy* **2022**, *167*, 113091. [CrossRef]
15. Alahmed, A.S.; Tong, L. On net energy metering X: Optimal prosumer decision, social welfare, and cross-subsidies. *IEEE Trans. Smart Grid* **2022**. [CrossRef]

16. Yamamoto, Y. Pricing electricity from residential photovoltaic systems: A comparison of feed-in tariffs, net metering, and net purchase and sale. *Solar Energy* **2012**, *86*, 2678–2685. [CrossRef]
17. Cohen, R.; Khermouch, G. The giant headache that is net energy metering. *Electr. J.* **2013**, *26*, 5–7.
18. Janko, S.A.; Arnold, M.R.; Johnson, N.G. Implications of high-penetration renewables for ratepayers and utilities in the residential solar photovoltaics (PV) market. *Appl. Energy* **2016**, *180*, 37–51. [CrossRef]
19. Costello, K.W.; Hemphill, R.C. Electric Utilities' 'Death Spiral': Hyperbole or reality. *Electr. J.* **2014**, *27*, 7–26. [CrossRef]
20. Kind, P. *Disruptive Challenges: Financial Implications and Strategic Response to a Changing Retail Electric Business*; EEI: Washington, DC, USA, 2013.
21. Laws, N.D.; Epps, B.P.; Perterson, S.O.; Laser, M.S.; Wanjiru, G.K. On the utility death spiral and the impact of utility rate structures on the adoption of residential solar photovoltaics and energy storage. *Appl. Energy* **2017**, *185*, 627–641. [CrossRef]
22. Muaafa, M.; Adjali, I.; Bean, P.; Fuentes, R.; Kimbrought, S.O.; Murphy, F.H. Can adoption of rooftop solar panels trigger a utility death spiral? A tale of two US cities. *Energy Res. Soc. Sci.* **2017**, *34*, 154–162. [CrossRef]
23. Borenstein, S. The economics of fixed cost recovery by utilities. *Electr. J.* **2016**, *29*, 5–12. [CrossRef]
24. Olivia, H.S.; MacGill, I.; Passey, R. Assessing the short-term revenue impacts of residential PV systems on electricity customers, retailers and network service providers. *Renew. Sust. Energ. Rev.* **2016**, *54*, 1494–1505. [CrossRef]
25. Venkatraman, A.; Thatte, A.A.; Xie, L. A smart meter data-driven distribution utility rate model for networks with prosumers. *Util. Policy* **2021**, *70*, 101212. [CrossRef]
26. Clastres, C.; Percebois, J.; Rebenaque, C.; Solier, B. Cross subsidies across electricity network users from renewable self-consumption. *Util. Policy* **2019**, *59*, 100925. [CrossRef]
27. Kubli, M. Squaring the sunny circle? On balancing distributive justice of power grid costs and incentives for solar prosumers. *Energy Policy* **2018**, *114*, 173–188. [CrossRef]
28. Nikolaidis, A.I.; Charalambous, C.A. Hidden financial implications of the net energy metering practice in an isolated power system: Critical review and policy insights. *Renew. Sust. Energ. Rev.* **2018**, *77*, 706–717. [CrossRef]
29. Picciariello, A.; Vergara, C.; Reneses, J.; Frías, P.; Söder, L. Electricity distribution tariffs and distributed generation: Quantifying cross-subsidies from consumers to prosumers. *Util. Policy* **2015**, *37*, 25–33. [CrossRef]
30. Burger, S.; Knittel, C.; Pérez-Arriaga, I. *Quantifying the Distributional Impacts of Rooftop Solar PV Adoption under Net Energy Metering*; MIT CEEPR: Cambridge, MA, USA, 2020.
31. Ansarin, M.; Ghiassi-Farrokhfal, Y.; Ketter, W.; Collins, J. Cross-subsidies among residential electricity prosumers from tariff design and metering infrastructure. *Energy Policy* **2020**, *145*, 111736. [CrossRef]
32. Fikru, M.G.; Canfield, C.I. A generic economic framework for electric rate design with prosumers. *Solar Energy* **2020**, *211*, 1325–1334. [CrossRef]
33. KEPCO. Available online: https://cyber.kepco.co.kr/ckepco/front/jsp/CY/E/E/CYEEHP00209.jsp (accessed on 4 January 2023).
34. KEPCO. *Statics of Electric Power in Korea 2019*; KEPCO: Naju, Republic of Korea, 2020.
35. Deng, G.; Newton, P. Assessing the impact of solar PV on domestic electricity consumption: Exploring the prospect of rebound effects. *Energy Policy* **2017**, *110*, 313–324. [CrossRef]
36. Havas, L.; Ballweg, J.; Penna, C.; Race, D. Power to change: Analysis of household participation in a renewable energy and energy efficiency programme in Central Australia. *Energy Policy* **2015**, *87*, 325–333. [CrossRef]
37. KPX (Korea Power Exchnage). Available online: https://epsis.kpx.or.kr/epsisnew/selectEkpoBftChart.do?menuId=020100&locale=eng (accessed on 4 January 2023).
38. Chung, M.H. Comparison of economic feasibility for efficient peer-to-peer electricity trading of PV equipped residential house in Korea. *Energies* **2020**, *13*, 3568. [CrossRef]
39. Hledik, R. Rediscovering residential demand charges. *Electr. J.* **2014**, *27*, 82–96. [CrossRef]